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(54) **SELECTIVE STIMULATION WITH COCHLEAR IMPLANTS**

SELEKTIVE STIMULIERUNG MIT COCHLEAIMPLANTATEN

STIMULATION SÉLECTIVE AVEC IMPLANTS COCHLÉAIRES

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Description

FIELD OF THE INVENTION

[0001] The present invention relates to cochlear implant systems, and more specifically, to techniques for coding electrical stimulation pulses in such systems.

BACKGROUND ART

[0002] A normal ear transmits sounds as shown in Figure 1 through the outer ear **101** to the tympanic membrane **102**, which moves the bones of the middle ear **103** (malleus, incus, and stapes) that vibrate the oval window and round window openings of the cochlea **104.** The cochlea **104** is a long narrow duct wound spirally about its axis for approximately two and a half turns. It includes an upper channel known as the scala vestibuli and a lower channel known as the scala tympani, which are connected by the cochlear duct. The cochlea **104** forms an upright spiraling cone with a center called the modiolar where the spiral ganglion cells of the acoustic nerve **113** reside. In response to received sounds transmitted by the middle ear **103**, the fluid-filled cochlea **104** functions as a transducer to generate electric pulses which are transmitted to the cochlear nerve **113**, and ultimately to the brain.

[0003] Hearing is impaired when there are problems in the ability to transduce external sounds into meaningful action potentials along the neural substrate of the cochlea **104.** To improve impaired hearing, auditory prostheses have been developed. For example, when the impairment is related to operation of the middle ear **103**, a conventional hearing aid may be used to provide acoustic-mechanical stimulation to the auditory system in the form of amplified sound. Or when the impairment is associated with the cochlea **104**, a cochlear implant with an implanted stimulation electrode can electrically stimulate auditory nerve tissue with small currents delivered by multiple electrode contacts distributed along the electrode.

[0004] Figure 1 also shows some components of a typical cochlear implant system which includes an external microphone that provides an audio signal input to an external signal processor **111** where various signal processing schemes can be implemented. The processed signal is then converted into a digital data format, such as a sequence of data frames, for transmission into the implant **108.** Besides receiving the processed audio information, the implant **108** also performs additional signal processing such as error correction, pulse formation, etc., and produces a stimulation pattern (based on the extracted audio information) that is sent through an electrode lead **109** to an implanted electrode array **110.**

[0005] Typically, this electrode array **110** includes multiple stimulation contacts **112** on its surface that provide selective stimulation of the cochlea **104.** Depending on context, the stimulation contacts **112** are also referred to as electrode channels. In cochlear implants today, a relatively small number of electrode channels are each associated with relatively broad frequency bands, with each stimulation contact **112** addressing a group of neurons through an electric stimulation pulse having a charge which is derived from the instantaneous amplitude of the signal envelope within that frequency band.

[0006] In some coding strategies, stimulation pulses are applied at a constant rate across all electrode channels, whereas in other coding strategies, stimulation pulses are applied at a channel-specific rate. Various specific signal processing schemes can be implemented to produce the electrical stimulation signals. Signal processing approaches that are well-known in the field of cochlear implants include continuous interleaved sampling (CIS) digital signal processing, channel specific sampling sequences (CSSS) digital signal processing, as described in U.S. Patent No. 6,348,070, , spectral peak (SPEAK) digital signal processing, and compressed analog (CA) signal processing.

[0007] For example, Figure 2 shows the major functional blocks in a typical cochlear implant signal processing system wherein band pass signals are processed and coding to generate electrode stimulation signals to stimulation electrodes in an implanted cochlear implant electrode array. Preprocessor Filter Bank **201** pre-processes the initial acoustic audio signal with a bank of band pass filters, each of which is associated with a specific band of audio frequencies so that the acoustic audio signal is filtered into some M band pass signals, B_1 to B_M where each signal corresponds to the band of frequencies for one of the band pass filters. Based on the tonotopic organization of the cochlea, each stimulation contact in the scala tympani often is associated with a specific band pass filter of the external filter bank. Figure 3 shows an example of a short time period of an audio speech signal from a microphone, and Figure 4 shows an acoustic microphone signal decomposed by band-pass filtering by a bank of filters into a set of signals.

[0008] The band pass signals B_1 to B_M are input to a Signal Processor **202** which extracts signal specific stimulation information-e.g., envelope information, phase information, timing of requested stimulation events, etc.-into a set of N stimulation channel signals S_1 to S_N that collectively represent the sound information that is present in the initial acoustic audio signal. Stimulation Coding Module **203** then converts the processed stimulation channel signals S_1 to S_N to produce a corresponding sequence of electrode stimulation signals A_1 to A_M that provide an optimal electric representation of the acoustic signal, while the Pulse Mapping and Shaping Module **204** then applies a linear mapping function (typically logarithmic) and pulse shaping of the electrode stimulation signals A_1 to A_M that is adapted to the needs of the individual implant user based on a post-surgical fitting process that determines patient-specific perceptual characteristics.

[0009] The output of the Pulse Mapping and Shaping

Module **204** is a set of electrode stimulation signals E_1 to E_M to the stimulation contacts in the implanted electrode array which stimulate the adjacent nerve tissue. Symmetrical biphasic current pulses are often applied for stimulation. In the specific case of a CIS system, the stimulation pulses are applied in a strictly non-overlapping sequence. Thus, as a typical CIS-feature, only one electrode channel is active at one time and the overall stimulation rate is comparatively high. For example, assuming an overall stimulation rate of 18 kpps and a 12 channel filter bank, the stimulation rate per channel is 1.5 kpps. Such a stimulation rate per channel usually is sufficient for adequate temporal representation of the envelope signal. The maximum overall stimulation rate is limited by the minimum phase duration per pulse. The phase duration cannot be chosen arbitrarily short, because the shorter the pulses, the higher the current amplitudes have to be to elicit action potentials in neurons, and current amplitudes are limited for various practical reasons. For an overall stimulation rate of 18 kpps, the phase duration is 27μs, which is near the lower limit. Each output of the CIS band pass filters can roughly be regarded as a sinusoid at the center frequency of the band pass filter which is modulated by the envelope signal. This is due to the quality factor ($Q \approx 3$) of the filters. In case of a voiced speech segment, this envelope is approximately periodic, and the repetition rate is equal to the pitch frequency.

[0010] In the existing CIS-strategy, only the signal envelopes are used for further processing, i.e., they contain the entire stimulation information. For each electrode channel, the signal envelope is represented as a sequence of biphasic pulses at a constant repetition rate. A characteristic feature of CIS is that this repetition rate (typically 1.5 kpps) is equal for all electrode channels and there is no relation to the center frequencies of the individual channels. It is intended that the repetition rate is not a temporal cue for the patient, i.e., it should be sufficiently high, so that the patient does not perceive tones with a frequency equal to the repetition rate. The repetition rate is usually chosen at greater than twice the bandwidth of the envelope signals (Nyquist theorem).

[0011] Another cochlear implant stimulation strategy that transmits fine time structure information is the Fine Structure Processing (FSP) strategy by Med-El. Zero crossings of the band pass filtered time signals are tracked, and at each negative to positive zero crossing a Channel Specific Sampling Sequence (CSSS) is started. Typically CSSS sequences are only applied on the first one or two most apical electrode channels, covering the frequency range up to 200 or 330 Hz. The FSP arrangement is described further in Hochmair I, Nopp P, Jolly C, Schmidt M, Schößer H, Garnham C, Anderson I, MED-EL Cochlear Implants: State of the Art and a Glimpse into the Future, Trends in Amplification, vol. 10, 201-219, 2006.

[0012] Many CI coding strategies use what is referred to as an N-of-M approach where only some number n electrode channels with the greatest amplitude are stimulated in a given sampling time frame. If, for a given time frame, the amplitude of a specific electrode channel remains higher than the amplitudes of other channels, then that channel will be selected for the whole time frame. Subsequently, the number of electrode channels that are available for coding information is reduced by one, which results in a clustering of stimulation pulses. Thus, fewer electrode channels are available for coding important temporal and spectral properties of the sound signal such as speech onset.

[0013] One method to reduce the spectral clustering of stimulation per time frame is the MP3000™ coding strategy by Cochlear Ltd, which uses a spectral masking model on the electrode channels. Another method that inherently enhances coding of speech onsets is the ClearVoice™ coding strategy used by Advanced Bionics Corp, which selects electrode channels having a high signal to noise ratio. U.S. Patent Publication 2005/0203589 describes how to organize electrode channels into two or more groups per time frame. The decision which electrode channels to select is based on the amplitude of the signal envelopes.

[0014] In addition to the specific processing and coding approaches discussed above, different specific pulse stimulation modes are possible to deliver the stimulation pulses with specific stimulation contacts -*i.e.* mono-polar, bi-polar, tri-polar, multi-polar, and phased-array stimulation. And there also are different stimulation pulse shapes-*i.e.* biphasic, symmetric triphasic, asymmetric triphasic pulses, or asymmetric pulse shapes. These various pulse stimulation modes and pulse shapes each provide different benefits; for example, higher tonotopic selectivity, smaller electrical thresholds, higher electric dynamic range, less unwanted side-effects such as facial nerve stimulation, etc. But some stimulation arrangements are quite power consuming, especially when neighboring stimulation contacts are used as current sinks. Up to 10 dB more charge might be required than with simple mono-polar stimulation concepts (if the power-consuming pulse shapes or stimulation modes are used continuously).

[0015] Another consideration as to stimulation pattern is the spread of the excitation pattern in the stimulated neural tissue. This excitation spread is a function of amplitude so that at relatively low stimulation levels near the hearing threshold level, the region of excited neurons is small, whereas at high stimulation levels, large populations throughout the cochlea are excited. *See, e.g.,* U.S. Patent 7,941,223. Excitation spread occurs both with acoustic excitation (as in normal hearing) and with electric stimulation of the neural tissue as in a cochlear implant.

[0016] Some literature in the field discusses stimulation modes intended to produce selective stimulation; *e.g.* U.S. Patent 7,899,547; EP 2482923, and Litvak et al., Loudness growth observed under partially tripolar stimulation: Model and data from cochlear implant listeners, J. Acoust. Soc. Am. 122 2, August 2007. Such literature takes into account the natural behavior of a level-dependent spread of excitation. At high perceptual levels, stimulation modes intending to generate focused stimulation, produce a spread of excitation that is quite similar to the spread of a simple mono-polar stimulation mode. For a wide spread of excitation, mono-polar stimulation is probably the most power-efficient mode, whereas at low stimulation levels, multi-polar stimulation is known to achieve the lowest spread of excitation, albeit in a less power efficient manner.

[0017] U.S. Patent application US 2014 074183 discusses enhancing spectral contrast for a cochlear implant listener that includes a time domain signal. A first transformation is applied to the detected time domain signal to convert the time domain signal to a frequency domain signal. A second transformation is applied to the frequency domain signal to express the frequency domain signal as a sum of two or more components, and a sensitivity of the cochlear implant listener to detect modulation of each component can be obtained.

SUMMARY OF THE INVENTION

[0018] Embodiments of the present invention are directed to a signal processing arrangement and corresponding method that generates electrode stimulation signals to stimulation contacts in a cochlear implant electrode array. A signal filter bank is configured to transform an input sound signal into band pass signals that each represent an associated frequency band of audio frequencies. A signal processing module is configured to process the band pass signals in a sequence of sampling time frames, wherein for each time frame, the processing includes performing a spectral feature analysis of the band pass signals, and dynamically assigning a stimulation focus pattern to one or more of the band pass signals based on the spectral feature analysis. A stimulation coding module is configured to code the processed band pass signals for each time frame to produce the electrode stimulation signals for delivery by the stimulation contacts to a region of adjacent auditory neural tissue.

[0019] In further specific embodiments, there may be a pulse mapping and shaping module that is configured to weight the electrode stimulation signals based on patient-specific stimulation characteristics.

[0020] The signal processing module may specifically be configured to dynamically assign a focused stimulation pattern to one or more of the band pass signals based on the spectral feature analysis so that the electrode stimulation signals are delivered to a region of adjacent auditory neural tissue that is limited by the stimulation focus pattern. For example, the focused stimulation pattern may be based on a tripolar stimulation mode or a phased array stimulation mode.

[0021] In addition or alternatively, the signal processing module may specifically be configured to dynamically assign an unfocused stimulation pattern to one or more of the band pass signals based on the spectral feature analysis so that the electrode stimulation signals are delivered to a region of adjacent auditory neural tissue that is not limited by the stimulation focus pattern. For example, the unfocused stimulation pattern may be based on a monopolar stimulation mode. The signal processing module may be configured to perform a spectral feature analysis of the band pass signals that includes an analysis of frequency spread of spectral features of a plurality of adjacent band pass signals.

BRIEF DESCRIPTION OF THE DRAWINGS

[0022]

Figure 1 shows a section view of a human ear with a typical auditory prosthesis system designed to deliver electric stimuli to the inner ear and acoustic stimuli at the ear canal.

Figure 2 shows various functional blocks in a continuous interleaved sampling (CIS) processing system.

Figure 3 shows an example of a short time period of an audio speech signal from a microphone.

Figure 4 shows an acoustic microphone signal decomposed by band-pass filtering by a bank of filters into a set of signals.

Figure 5 shows an example of a band pass signal spectrum assignment graph according to a first scenario.

Figure 6 shows an example of a band pass signal spectrum assignment graph according to a second scenario.

Figure 7 shows an example of a band pass signal spectrum assignment graph according to a third scenario.

Figure 8 shows an example of a band pass signal spectrum assignment graph according to a fourth scenario.

DETAILED DESCRIPTION OF SPECIFIC EMBODIMENTS

[0023] The width of spectral features has been accounted for in coding strategies which are based on the N-of-M principle where N channels which higher amplitudes are selected for stimulation. Channels which contain dominant spectral features are more likely to be selected. In presence of a broad and dominant spectral feature which is spread over adjacent channels, a less dominant and narrow spectral feature is likely to be omitted. Besides these implications related to channel selection based on amplitudes only, no further measure is taken to code the spectral widths of the features by means of manipulating stimulation pulses or stimulation modes, e.g. monopolar, tripolar.

[0024] Embodiments of the present invention take account of level-dependent spread of excitation based on assigning focused or unfocused stimulation patterns to stimulation channels as a function of a channel independent analysis of the spectral widths of spectral features of the digital input signal. The selected focused/unfocused stimulation patterns may be applied by the signal coding stage which applies a selected coding strategy to present the assigned stimulation patterns to the stimulation electrodes of the CI electrode contacts. A focused stimulation pattern may be realized (for example) by tripolar or phased array stimulation modes to deliver electrode stimulation signals to a limited region of adjacent neural auditory tissue. Alternatively, an unfocused stimulation focus pattern may be realized by (for example) by conventional monopolar stimulation modes to deliver electrode stimulation signals to a region of adjacent neural auditory tissue that is not limited by the stimulation focus pattern. In some specific embodiments, the dynamic focusing assignment may result in a mixture of focused and unfocused stimulation patterns.

[0025] When the focusing assignment is done dynamically, overall power consumption by the system may be comparable to the power consumption of existing cochlear implant systems. In some embodiments, the assignment stimulation patterns may occur dynamically such that energy consuming focused stimulation patterns are assigned rather rarely. And in contrast to previous arrangements for handling spread of excitation, embodiments of the present invention are specific to the signal processing stage, and so the invention is not limited to any particular specific coding strategy (such as CIS, FSP, FSP 4, N-of-M, etc.). And since some features of the audio signal that are analyzed by the signal processing stage may be band-specific, while other signal features may be characteristic of portions of the input signal that may be larger or smaller than a single band pass channel. Therefore (and contrary to the suggestion of the prior art), where the focus assignment step analyzes the frequency spread (FS) of spectral features over a plurality of bands of the band pass signals.

[0026] Embodiments of the present invention are directed to a signal processing arrangement and corresponding method that generates electrode stimulation signals to stimulation contacts in a cochlear implant electrode array based on determining the frequency spread or spectral features of the band pass signals. As in the arrangement discussed above with respect to Figure 2, a preprocessor signal filter bank **201** can be configured to transform an input sound signal into band pass signals B_1 to B_M that each represent an associated frequency band of audio frequencies.

[0027] Then the signal processing module **202** can be configured to process the band pass signals B_1 to B_M in a sequence of sampling time frames that includes performing a spectral feature analysis of the band pass signals such as an analysis of frequency spread of spectral features of the adjacent band pass signals. Based on that spectral feature analysis, the signal processing module **202** then dynamically assigns a stimulation focus pattern to one or more of the band pass signals. The signal processing module **202** may specifically be configured to dynamically assign a focused stimulation pattern such as a tripolar stimulation mode or a phased array stimulation mode to one or more of the band pass signals B_1 to B_M based on the spectral feature analysis so that the electrode stimulation signals are delivered to a region of adjacent auditory neural tissue that is limited by the stimulation focus pattern. In addition or alternatively, the signal processing module **202** may specifically be configured to dynamically assign an unfocused stimulation pattern such as a monopolar stimulation mode to one or more of the band pass signals B_1 to B_M based on the spectral feature analysis so that the electrode stimulation signals are delivered to a region of adjacent auditory neural tissue that is not limited by the stimulation focus pattern.

[0028] The stimulation coding module **203** then is configured to convert the processed stimulation channel signals S_1 to S_N to produce a corresponding sequence of electrode stimulation signals A_1 to A_M that provide an optimal electric representation of the acoustic signal, while the Pulse Mapping and Shaping Module **204** then applies a linear mapping function (typically logarithmic) and pulse shaping of the electrode stimulation signals A_1 to A_M that is adapted to the needs of the individual implant user based on a post-surgical fitting process that determines patient-specific perceptual characteristics.

[0029] In the following discussion, the focused stimulation pattern specifically discussed is the tripolar stimulation mode, which comprises a stimulation pulse of a given polarity applied by a given stimulation contact, accompanied by offsetting stimulation pulses of opposite polarity on the adjacent neighboring stimulation contacts (all three pulses being charge balanced to avoid net DC current). Since these current sources and sinks are physically close together, and since the endolymph fluid in the cochlea has high electrical conductivity, the region of neural tissue that is stimulated is fairly focused and limited. Conventional monopolar stimulation, by contrast, is used as the unfocused stimulation focus pattern and exploits the electrical stimulation that results from a single intracochlear stimulation contact together with a remote extracochlear ground electrode contact that completes the current path, and the resulting region of neural tissue that is stimulated is fairly unfocused and not limited.

[0030] More specifically with respect to the dynamic focusing assignment performed by the signal processing module **202**, it may initially may process the incoming band pass signals B_1 to B_M such that for each frequency band pass signal *Bn,* a characteristic amplitude level A_n

is determined, which may specifically be the amplitude value of the center frequency of the frequency band or a mean amplitude value of the band. And for each band *Bn,* the differences are calculated between the characteristic amplitude levels of adjacent bands are calculated, including the sign of the difference which determines whether the slope of the amplitude curve is rising or falling: D1 = (A_{n-1} - A_n) and D2 = (A_n - A_{n+1}). Then for each band Bn, the two differences to the left and right neighbors, D1 and D2, are compared and a focused/unfocused assignment is made.

[0031] Figure 5 shows band pass amplitude signals for a first scenario where, if the absolute value of only one of the amplitude differences D1 and D2 is greater than some given first focus threshold value X, that band pass channel may be evaluated as important ("i" in Fig. 5), and have assigned to it an unfocused stimulation pattern; see channels 2, 3, 5, and 6. The first focus threshold value X can be predetermined or dynamically determined, e.g. by averaging the actual differences D between all adjacent channels, or as a fraction of the amplitude of the maximum channel.

[0032] If the absolute values of both adjacent channel differences D1 and D2 are larger than the focus threshold value X, and the sign of the differences is different (one is positive and the other negative), then that channel may evaluated important ("i") and a focused stimulation pattern may be assigned; see e.g., channels 4 and 10.

[0033] If the absolute values of both differences D1 and D2 are smaller than a second focus threshold value Y, and the absolute value of the characteristic amplitude level of this band (A_n) is greater than another third focus threshold value, W, then that channel is evaluated important ("i") and an unfocused stimulation pattern may be assigned; see, e.g., Figure 8, channel 3. Again, either both of the second focus threshold value, Y, and the third focus threshold value, W, can be fixed, or dynamically determined; e.g., adjusted relative to the amplitude of the maximum channel. Any or all of the thresholds X, Y, and W also might be a relative threshold on a logarithmic scale, e.g. ½ / 2 or 6 dB.

[0034] All the other band pass channels may be evaluated as unimportant ("u") and no focused/unfocused stimulation pattern may be assigned (see e.g., Fig. 5, channels 8 and 12) or the stimulation focus pattern may be determined based on the neighboring channels (e.g., Fig. 5, channels 9 and 11).

[0035] There needs to be different rules for determining the stimulation focus patterns for the stimulation contacts at the apical and basal ends of the electrode array. One way to handle these is to provide additional analysis-only filter bands on the "empty" sides of these stimulation contacts, and then follow the same analysis rules set forth above. Thus, in the specific examples set forth in Figures 5-9, Channels 1 and 12 are such empty analysis-only frequency bands, and the implanted electrode array has ten stimulation contacts that correspond to Channels 2-11 in those Figures.

[0036] As can be seen in Figure 5, conflicting results can arise when determining a stimulation mode to realize focused or unfocused stimulation. For example, if the applied stimulation modes are monopolar for unfocused stimulation and tripolar for focused stimulation, Channels 3 and 5 in Figure 5 are assigned for monopolar stimulation based on the evaluation described above of their own channels, while at the same time they have been assigned for the opposite polarity stimulation portion of the tripolar stimulation mode based on the evaluation of their common neighboring Channel 4. In a case where simultaneous stimulation of the stimulation channels is desired, another rule may be applied which follows the principle that the highest characteristic amplitude level of the involved channels (Channel 4 in this case) overrules the other focusing mode assignments of Channels 3 and 5. This would lead to tripolar stimulation on Channels 3, 4 and 5 with one polarity on Channel 4 and opposite polarities on Channels 3 and 5, instead of monopolar stimulation on Channels 3 and 5. In a sequential stimulation mode arrangement, first the focused stimulation is applied with Channel 4 in the center (focus) and Channels 3 and 5 as the adjacent current sinks. Then, in the next time frame, monopolar stimulation of Channel 3, and then in the next time frame, monopolar stimulation of Channel 5 can be applied, where the sequential order can be changed.

[0037] As can be seen from comparison of the assignment scenarios depicted in Figures 6 and 7, the assignment of focused or unfocused stimulation (denoted as "m" for monopolar and "tri" for tripolar) may not reflect the actual spectrum of the digital audio signal (solid lines). Figure 6 shows a single broad peak at Channels 3 and 4 to which monopolar stimulation pattern would be assigned, whereas Figure 7 shows two adjacent sharp peaks on Channels 3 and 4 to which tripolar stimulation patterns should be assigned according to the above description. With the number of band pass signals shown in the Figures, the above focusing assignment rules would assign unfocused (monopolar) stimulation patterns to both channels. The number of band pass signals may be increased in order to increase the processing resolution. In that case, an additional focusing assignment rule would be used to assign the *m* band pass signals processed in the signal processing module onto the *k* (*m*>*k*) stimulation channels in the implanted electrode array. If the frequency analysis is fine enough to resolve the frequency spectrum shown in Figure 7, then sequential focused stimulation can be performed with Channels 3 and 4; for example, in one time frame a tripolar stimulation mode would be applied with Channel 3 in the center and Channels 2 and 4 as current sinks, and in the next time frame, focused stimulation with Channel 4 in the focus and Channels 3 and 5 as current sinks is applied.

[0038] Alternatively, the first rule of the above discussion may be amended by an additional rule, that if the first focus threshold X is even greater than another specific focus threshold value Z, then a focused stimulation pattern may be assigned. The Z-threshold can be fixed or dynamically adjusted relative to the amplitude of the maximum channel. This amended assignment rule would result in unfocused stimulation patterns for Channels 3 and 4 in the scenario shown in Figure 6, and focused stimulation patterns for these channels in scenario 3. If tripolar stimulation mode is chosen for the focused stimulation pattern, then a pattern with same polarities on Channels 3 and 4 have to be used and opposite polarities on Channels lower than 3 and higher than 4.

[0039] In the foregoing discussion, the assignment of focused or unfocused stimulation pattern has been described as a sort of digital process, i.e. either focused or unfocused. Some embodiments may be based on a smooth transition between these two stimulation patterns, or a number of intermediate states may be possible as well. Similarly, depending on the actual values of the amplitude differences D1 and D2, a mixture of focused and unfocused stimulation also may be assigned. For example, partial tripolar and partial monopolar stimulation may be assigned at the same time to the same stimulation channel. So if D1 and D2 are large, a pure tripolar stimulation pattern may be assigned (e.g. Figures 6 and 7, Channel 10). Or if D1 and D2 are lower (e.g. Figures 6 and 7, Channel 7), then a mixture of stimulation patterns may be assigned.

[0040] In embodiments of the present invention, the upfront determination of the location and width of band pass filters of the implant system is no longer critical. In existing cochlear implant systems, the band pass filters are chosen such that the expected formants of human voices are well within the frequency bands. And if the design choice is successful, then each pass band signal can be individually analyzed. But speech formant frequencies vary strongly from one person to another, and non-speech sound signals such as music may be important in some situations. This limitation can be avoided in embodiments of the present invention by analyzing multiple frequency bands at once as discussed above, to reliably identify the important frequency features of a sensed sound signal.

[0041] Embodiments of the present invention can also realize a significant reduction of power consumption as compared to the combination of conventional existing coding strategies, using more accurate but power consuming stimulation modes. Power-consuming stimulation modes will only be applied to limited portions of the input sound signal. An enhancement of spectro-temporal features at low levels as well as a more natural change of spread of excitation over levels can be modelled with the system.

[0042] Embodiments of the invention may be implemented in part any conventional computer programming language. For example, preferred embodiments may be implemented in a procedural programming language (*e.g.*, "C") or an object oriented programming language (*e.g.*, "C++", Python). Alternative embodiments of the invention may be implemented as pre-programmed hardware elements, other related components, or as a combination of hardware and software components.

[0043] Embodiments can be implemented in part as a computer program product for use with a computer system. Such implementation may include a series of computer instructions fixed either on a tangible medium, such as a computer readable medium (*e.g.*, a diskette, CD-ROM, ROM, or fixed disk) or transmittable to a computer system, via a modem or other interface device, such as a communications adapter connected to a network over a medium. The medium may be either a tangible medium (*e.g.*, optical or analog communications lines) or a medium implemented with wireless techniques (*e.g.*, microwave, infrared or other transmission techniques). The series of computer instructions embodies all or part of the functionality previously described herein with respect to the system. Those skilled in the art should appreciate that such computer instructions can be written in a number of programming languages for use with many computer architectures or operating systems. Furthermore, such instructions may be stored in any memory device, such as semiconductor, magnetic, optical or other memory devices, and may be transmitted using any communications technology, such as optical, infrared, microwave, or other transmission technologies. It is expected that such a computer program product may be distributed as a removable medium with accompanying printed or electronic documentation (*e.g.*, shrink wrapped software), preloaded with a computer system (*e.g.*, on system ROM or fixed disk), or distributed from a server or electronic bulletin board over the network (*e.g.*, the Internet or World Wide Web). Of course, some embodiments of the invention may be implemented as a combination of both software (*e.g.*, a computer program product) and hardware. Still other embodiments of the invention are implemented as entirely hardware, or entirely software (*e.g.*, a computer program product).

[0044] Although various exemplary embodiments of the invention have been disclosed, it should be apparent to those skilled in the art that various changes and modifications can be made which will achieve some of the advantages of the invention without departing from the true scope of the invention.

Claims

1. A method of signal processing for generating electrode stimulation signals for stimulation contacts in an implanted cochlear implant electrode array, the method comprising:

   transforming an input sound signal into a plurality of band pass signals each representing an associated frequency band of audio frequencies;
   processing the band pass signals in a sequence of sampling time frames, wherein for each time

frame, the processing includes:

i. performing a spectral feature analysis of the band pass signals, including determining a difference in amplitude between each band pass signal and that of adjacent band pass signals, and

ii. dynamically assigning a stimulation focus pattern to one or more of the band pass signals based on whether the difference in amplitude between each band pass signal and its adjacent band pass signals is greater than a focus threshold values; and

coding the processed band pass signals for each time frame to produce the electrode stimulation signals.

2. The method according to claim 1, further comprising: weighting the electrode stimulation signals based on patient-specific stimulation characteristics.

3. The method according to claim 1, wherein dynamically assigning the stimulation focus pattern includes dynamically assigning a focused stimulation pattern to one or more of the band pass signals based on the spectral feature analysis so that the electrode stimulation signals are delivered to a region of adjacent auditory neural tissue that is limited by the stimulation focus pattern.

4. The method according to claim 3, wherein the focused stimulation pattern is based on a tripolar stimulation mode.

5. The method according to claim 3, wherein the focused stimulation pattern is based on a phased array stimulation mode.

6. The method according to claim 1, wherein dynamically assigning the stimulation focus pattern includes dynamically assigning an unfocused stimulation pattern to one or more of the band pass signals based on the spectral feature analysis so that the electrode stimulation signals are delivered to a region of adjacent auditory neural tissue that is not limited by the stimulation focus pattern.

7. The method according to claim 6, wherein the unfocused stimulation pattern is based on a monopolar stimulation mode.

8. The method according to claim 1, wherein the spectral feature analysis of the band pass signals includes an analysis of frequency spread of spectral features of a plurality of adjacent band pass signals.

9. A signal processing arrangement for generating electrode stimulation signals to stimulation contacts in an implanted cochlear implant electrode array, the arrangement comprising:

a signal filter bank configured to transform an input sound signal into a plurality of band pass signals each representing an associated frequency band of audio frequencies;

a signal processing module configured to process the band pass signals in a sequence of sampling time frames, wherein for each time frame, the processing includes:

i. performing a spectral feature analysis of the band pass signals, including determining a difference in amplitude between each band pass signal and that of adjacent band pass signals, and

ii. dynamically assigning a stimulation focus pattern to one or more of the band pass signals based on whether the difference in amplitude between each band pass signal and its adjacent band pass signals is greater than a focus threshold value; and

a stimulation coding module configured to code the processed band pass signals for each time frame to produce the electrode stimulation signals for delivery by the stimulation contacts to a region of adjacent auditory neural tissue.

10. The arrangement according to claim 9, further comprising:
a pulse mapping and shaping module configured to weight the electrode stimulation signals based on patient-specific stimulation characteristics.

11. The arrangement according to claim 9, wherein the signal processing module configured to dynamically assign a focused stimulation pattern to one or more of the band pass signals based on the spectral feature analysis so that the electrode stimulation signals are delivered to a region of adjacent auditory neural tissue that is limited by the stimulation focus pattern.

12. The arrangement according to claim 11, wherein the focused stimulation pattern is based on a tripolar stimulation mode.

13. The arrangement according to claim 11, wherein the focused stimulation pattern is based on a phased array stimulation mode.

14. The arrangement according to claim 9, wherein the signal processing module configured to dynamically assign an unfocused stimulation pattern to one or more of the band pass signals based on the spectral feature analysis so that the electrode stimulation signals are delivered to a region of adjacent auditory neural tissue that is not limited by the stimulation focus pattern.

15. The arrangement according to claim 14, wherein the unfocused stimulation pattern is based on a monopolar stimulation mode.

16. The arrangement according to claim 9, wherein the signal processing module configured to perform a spectral feature analysis of the band pass signals that includes an analysis of frequency spread of spectral features of a plurality of adjacent band pass signals.

Patentansprüche

1. Verfahren zur Signalverarbeitung zur Erzeugung von Elektrodenstimulationssignalen für Stimulationskontakte in einem implantierten Cochleaimplantat-Elektrodenarray, wobei das Verfahren umfasst:

Umwandeln eines Eingangstonsignals in mehrere Bandpasssignale, die jeweils ein zugeordnetes Frequenzband von Audiofrequenzen darstellen;
Verarbeiten der Bandpasssignale in einer Sequenz von Abtastzeitrahmen, wobei die Verarbeitung für jeden Zeitrahmen aufweist:

i. Durchführen einer Spektralmerkmalsanalyse der Bandpasssignale, einschließlich Bestimmen einer Differenz in der Amplitude zwischen jedem Bandpasssignal und der von benachbarten Bandpasssignalen, und
ii. dynamisches Zuweisen eines Stimulationsfokusmusters zu einem oder mehreren der Bandpasssignale basierend darauf, ob die Differenz in der Amplitude zwischen jedem Bandpasssignal und seinen benachbarten Bandpasssignalen größer als ein Fokusschwellenwert ist; und

Codieren der verarbeiteten Bandpasssignale für jeden Zeitrahmen, um die Elektrodenstimulationssignale zu erzeugen.

2. Verfahren nach Anspruch 1, ferner umfassend: Gewichten der Elektrodenstimulationssignale basierend auf patientenspezifische Stimulationseigenschaften.

3. Verfahren nach Anspruch 1, wobei das dynamische Zuweisen des Stimulationsfokusmusters dynamisches Zuweisen eines fokussierten Stimulationsmusters zu einem oder mehreren der Bandpasssignale basierend auf der Spektralmerkmalsanalyse aufweist, so dass die Elektrodenstimulationssignale in eine Region von benachbartem auditorischen Nervengewebe geliefert werden, das durch das Stimulationsfokusmuster begrenzt ist.

4. Verfahren nach Anspruch 3, wobei das fokussierte Stimulationsmuster auf einem tripolaren Stimulationsmodus basiert.

5. Verfahren nach Anspruch 3, wobei das fokussierte Stimulationsmuster auf einem Phased-Array-Stimulationsmodus basiert.

6. Verfahren nach Anspruch 1, wobei das dynamische Zuweisen des Stimulationsfokusmusters dynamisches Zuweisen eines nicht fokussierten Stimulationsmusters zu einem oder mehreren der Bandpasssignalen basierend auf der Spektralmerkmalsanalyse aufweist, so dass die Elektrodenstimulationssignale in eine Region von benachbartem auditorischen Nervengewebe geliefert werden, das nicht durch das Stimulationsfokusmuster begrenzt ist.

7. Verfahren nach Anspruch 6, wobei das nicht fokussierte Stimulationsmuster auf einem monopolaren Stimulationsmodus basiert.

8. Verfahren nach Anspruch 1, wobei die Spektralmerkmalanalyse der Bandpasssignale eine Analyse einer Frequenzspreizung von Spektralmerkmalen mehrerer benachbarter Bandpasssignale aufweist.

9. Signalverarbeitungsanordnung zur Erzeugung von Elektrodenstimulationssignalen für Stimulationskontakte in einem implantierten Cochleaimplantat-Elektrodenarray, wobei die Anordnung umfasst:

eine Signalfilterbank, die konfiguriert ist, ein Eingangstonsignal in mehrere Bandpasssignale umzuwandeln, die jeweils ein zugeordnetes Frequenzband von Audiofrequenzen darstellen;
ein Signalverarbeitungsmodul, das konfiguriert ist, die Bandpasssignale in einer Sequenz von Abtastzeitrahmen zu verarbeiten, wobei die Verarbeitung für jeden Zeitrahmen aufweist:

i. Durchführen einer Spektralmerkmalsanalyse der Bandpasssignale, einschließlich Bestimmen einer Differenz in der Amplitude zwischen jedem Bandpasssignal und der von benachbarten Bandpasssignalen, und
ii. dynamisches Zuweisen eines Stimulationsfokusmusters zu einem oder mehreren der Bandpasssignale basierend darauf, ob die Differenz in der Amplitude zwischen jedem Bandpasssignal und seinen benachbarten Bandpasssignalen größer als ein Fokusschwellenwert ist; und

ein Stimulationscodierungsmodul, das konfiguriert ist, die verarbeiteten Bandpasssignale für jeden Zeitrahmen zu codieren, um die Elektrodenstimulationssignale zur Lieferung durch die Stimulationskontakte in eine Region von benachbartem auditorischen Nervengewebes zu erzeugen.

10. Anordnung nach Anspruch 9, ferner umfassend: ein Pulsabbildungs- und -formungsmodul, das konfiguriert ist, die Elektrodenstimulationssignale basierend auf patientenspezifischen Stimulationseigenschaften zu gewichten.

11. Anordnung nach Anspruch 9, wobei das Signalverarbeitungsmodul konfiguriert ist, einem oder mehreren der Bandpasssignale basierend auf der Spektralmerkmalsanalyse dynamisch ein fokussiertes Stimulationsmuster zuzuweisen, so dass die Elektrodenstimulationssignale in eine Region von benachbartem auditorischen Nervengewebe geliefert werden, das durch das Stimulationsfokusmuster begrenzt ist.

12. Anordnung nach Anspruch 11, wobei das fokussierte Stimulationsmuster auf einem tripolaren Stimulationsmodus basiert.

13. Anordnung nach Anspruch 11, wobei das fokussierte Stimulationsmuster auf einem Phased-Array-Stimulationsmodus basiert.

14. Anordnung nach Anspruch 9, wobei das Signalverarbeitungsmodul konfiguriert ist, einem oder mehreren der Bandpasssignale basierend auf der Spektralmerkmalsanalyse ein nicht fokussiertes Stimulationsmuster dynamisch zuzuweisen, so dass die Elektrodenstimulationssignale in eine Region von benachbartem auditorischen Neuralgewebe geliefert werden, das nicht durch das Stimulationsfokusmuster begrenzt ist.

15. Anordnung nach Anspruch 14, wobei das nicht fokussierte Stimulationsmuster auf einem monopolaren Stimulationsmodus basiert.

16. Anordnung nach Anspruch 9, wobei das Signalverarbeitungsmodul konfiguriert ist, eine Spektralmerkmalsanalyse der Bandpasssignale durchzuführen, die eine Analyse einer Frequenzspreizung von Spektralmerkmalen mehrerer benachbarter Bandpasssignale aufweist.

Revendications

1. Procédé de traitement de signaux pour générer des signaux de stimulation d'électrode pour des contacts de stimulation dans un réseau d'électrodes d'implant cochléaire implanté, le procédé comprenant :

la transformation d'un signal sonore d'entrée en une pluralité de signaux passe-bande représentant chacun une bande de fréquence associée de fréquences audio ;
le traitement des signaux passe-bande dans une séquence d'intervalles de temps d'échantillonnage, pour chaque intervalle de temps, le traitement comprenant :

i. la réalisation d'une analyse des caractéristiques spectrales des signaux passe-bande, comprenant la détermination d'une différence d'amplitude entre chaque signal passe-bande et celui des signaux passe-bande adjacents, et
ii. l'affectation dynamique d'un motif de mise au point de stimulation à un ou plusieurs des signaux passe-bande sur la base du fait que la différence d'amplitude entre chaque signal passe-bande et ses signaux passe-bande adjacents est supérieure ou non à une valeur seuil de mise au point ; et

le codage des signaux passe-bande traités pour chaque intervalle de temps afin de produire les signaux de stimulation d'électrode.

2. Procédé selon la revendication 1, comprenant en outre :
la pondération des signaux de stimulation d'électrode sur la base des caractéristiques de stimulation spécifiques au patient.

3. Procédé selon la revendication 1, l'affectation dynamique du motif de mise au point de stimulation comprenant l'affectation dynamique d'un motif de stimulation mis au point à un ou plusieurs des signaux passe-bande sur la base de l'analyse des caractéristiques spectrales de sorte que les signaux de stimulation d'électrode sont délivrés à une région du tissu neural auditif adjacent qui est limitée par le motif de mise au point de stimulation.

4. Procédé selon la revendication 3, le motif de stimulation mis au point étant basé sur un mode de stimulation tripolaire.

5. Procédé selon la revendication 3, le motif de stimulation mis au point étant basé sur un mode de stimulation à réseau de phases.

6. Procédé selon la revendication 1, l'affectation dynamique du motif de mise au point de stimulation comprenant l'affectation dynamique d'un motif de stimulation non mis au point à un ou plusieurs des signaux passe-bande sur la base de l'analyse des caractéristiques spectrales de sorte que les signaux de stimulation d'électrode sont délivrés à une région du tissu neural auditif adjacent qui n'est pas limitée par le motif de mise au point de stimulation.

7. Procédé selon la revendication 6, le motif de stimulation non mis au point étant basé sur un mode de stimulation monopolaire.

8. Procédé selon la revendication 1, l'analyse des caractéristiques spectrales des signaux passe-bande comprenant une analyse de la dispersion en fréquence des caractéristiques spectrales d'une pluralité de signaux passe-bande adjacents.

9. Agencement de traitement de signal pour générer des signaux de stimulation d'électrode à des contacts de stimulation dans un réseau d'électrodes d'implant cochléaire implanté, l'agencement comprenant :

une banque de filtres de signaux configurée pour transformer un signal sonore d'entrée en une pluralité de signaux passe-bande représentant chacun une bande de fréquence associée de fréquences audio ;
un module de traitement de signaux configuré pour traiter les signaux passe-bande dans une séquence d'intervalles de temps d'échantillonnage, pour chaque intervalle de temps, le traitement comprenant :

i. la réalisation d'une analyse des caractéristiques spectrales des signaux passe-bande, comprenant la détermination d'une différence d'amplitude entre chaque signal passe-bande et celui des signaux passe-bande adjacents, et
ii. l'affectation dynamique d'un motif de mise au point de stimulation à un ou plusieurs des signaux passe-bande sur la base du fait que la différence d'amplitude entre chaque signal passe-bande et ses signaux passe-bande adjacents est supérieure à une valeur seuil de mise au point ; et

un module de codage de stimulation configuré pour coder les signaux passe-bande traités pour chaque intervalle de temps afin de produire les signaux de stimulation d'électrode à délivrer par les contacts de stimulation à une région d'un tissu neural auditif adjacent.

10. Agencement selon la revendication 9, comprenant en outre :
un module de mise en forme et de mise en correspondance des impulsions configuré pour pondérer les signaux de stimulation des électrodes sur la base des caractéristiques de stimulation propres au patient.

11. Agencement selon la revendication 9, le module de traitement de signal étant configuré pour affecter dynamiquement un motif de stimulation mis au point à un ou plusieurs des signaux passe-bande sur la base de l'analyse des caractéristiques spectrales de sorte que les signaux de stimulation d'électrode sont délivrés à une région de tissu neural auditif adjacent qui est limitée par le motif de mise au point de stimulation.

12. Agencement selon la revendication 11, le motif de stimulation mis au point étant basé sur un mode de stimulation tripolaire.

13. Agencement selon la revendication 11, le motif de stimulation mis au point étant basé sur un mode de stimulation à réseau phasé.

14. Agencement selon la revendication 9, le module de traitement de signal étant configuré pour affecter dynamiquement un motif de stimulation non mis au point à un ou plusieurs des signaux passe-bande sur la base de l'analyse des caractéristiques spectrales de sorte que les signaux de stimulation d'électrode sont délivrés à une région du tissu neural auditif adjacent qui n'est pas limitée par le motif de mise au point de stimulation.

15. Agencement selon la revendication 14, le motif de stimulation non mis au point étant basé sur un mode de stimulation monopolaire.

16. Agencement selon la revendication 9, le module de traitement de signal étant configuré pour réaliser une analyse des caractéristiques spectrales des signaux passe-bande qui comprend une analyse de la dispersion en fréquence des caractéristiques spectrales d'une pluralité de signaux passe-bande adjacents.

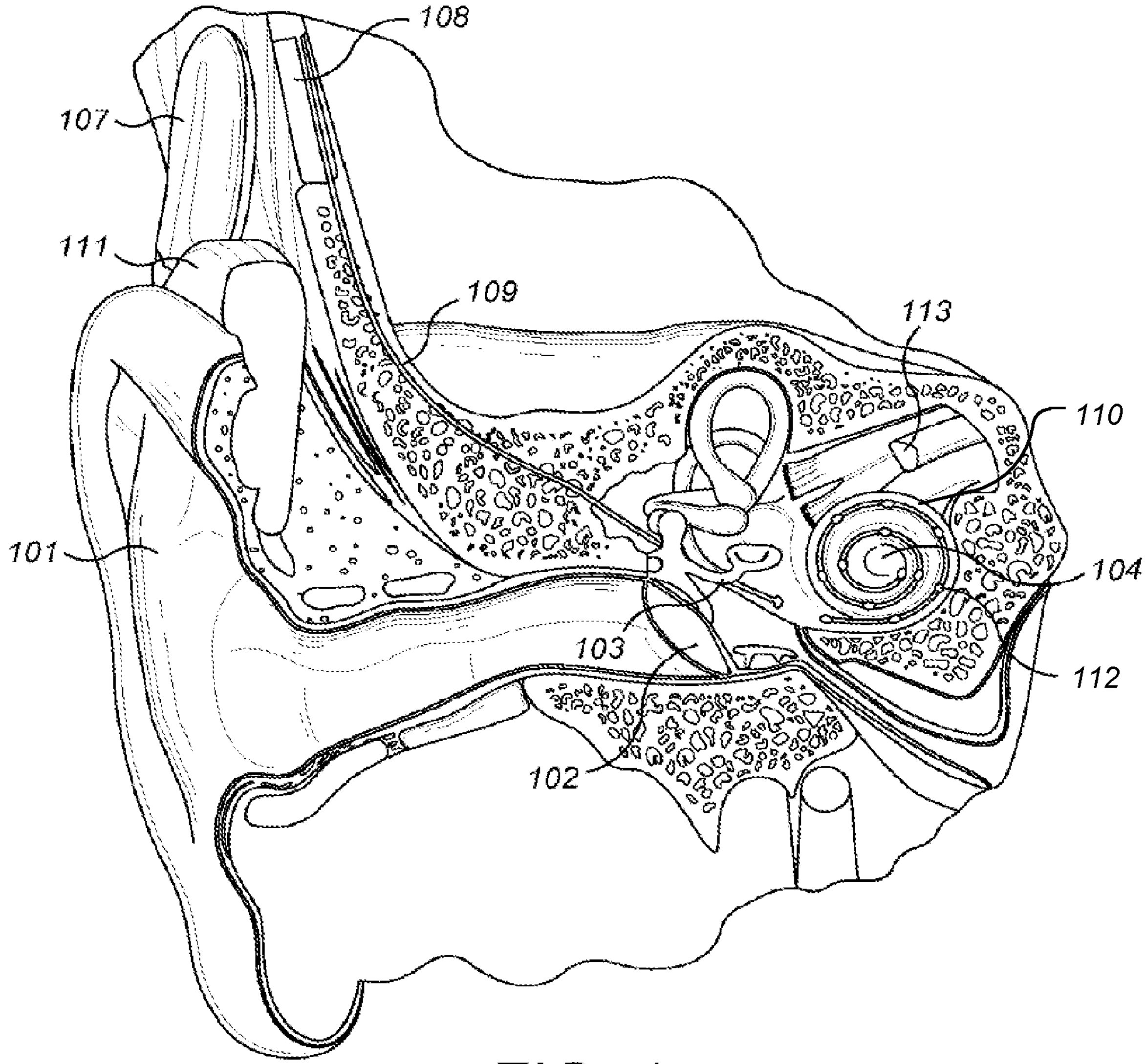


FIG. 1

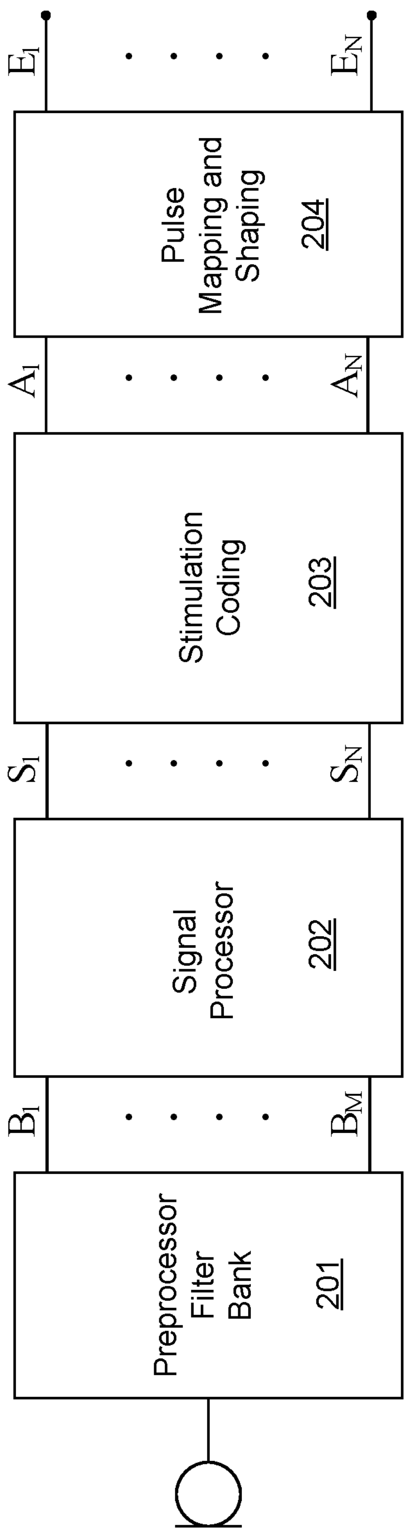
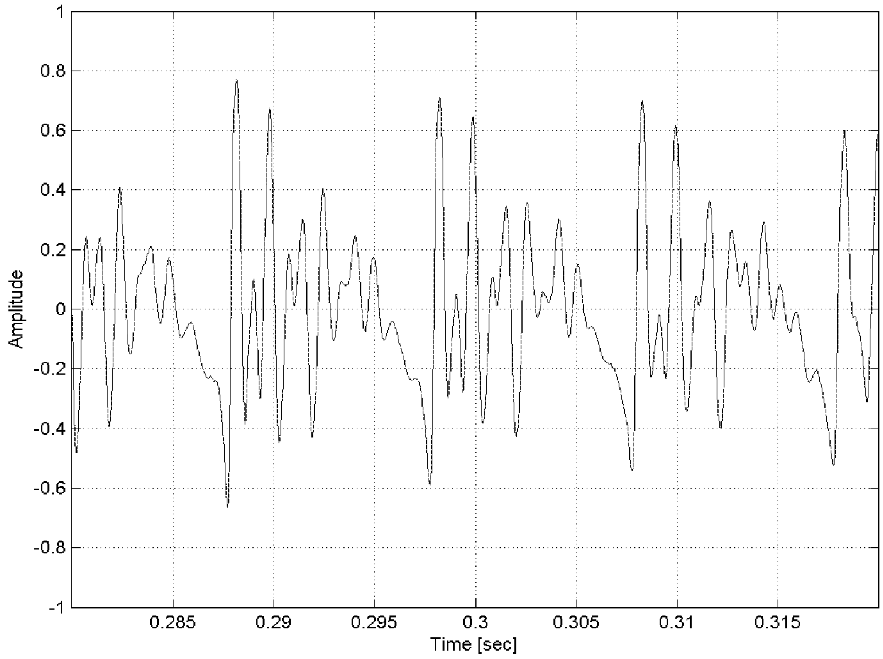

E_1
E_N
Pulse Mapping and Shaping
204
A_1
A_N
Stimulation Coding
203
S_1
S_N
Signal Processor
202
B_1
B_M
Preprocessor Filter Bank
201

Fig. 2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0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
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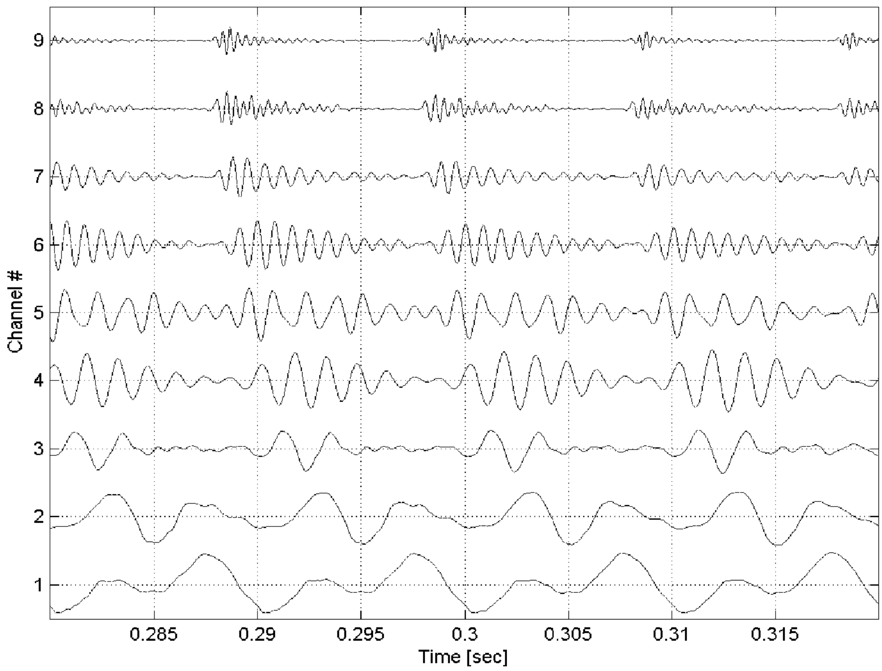
0.29
0.295
0.3
0.305
0.31
0.315
Time [sec]

FIG. 3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8
7
6
5
4
3
2
1
Channel #
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0.29
0.295
0.3
0.305
0.31
0.315
Time [sec]

FIG. 4

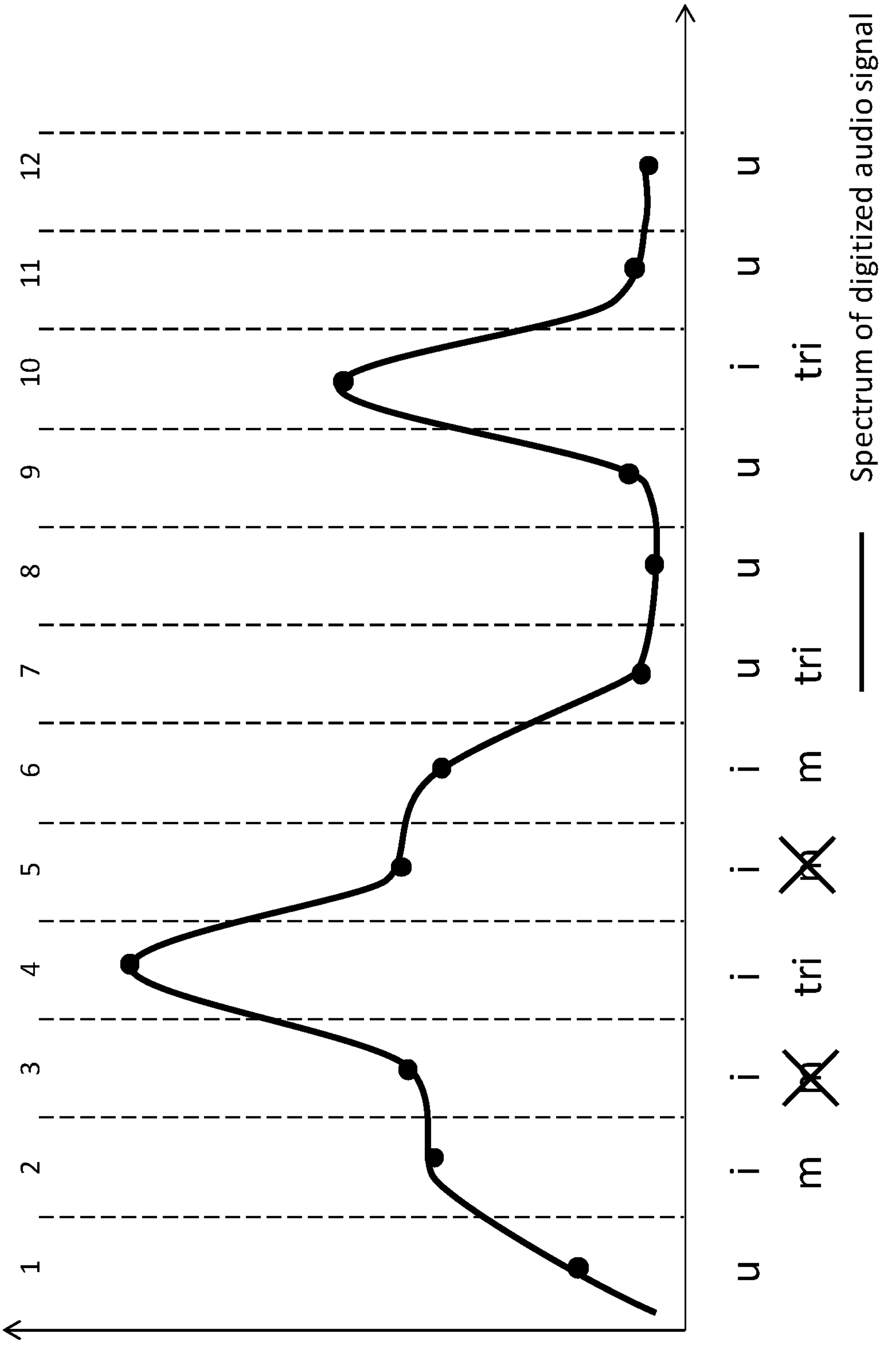

1 2 3 4 5 6 7 8 9 10 11 12
u i i i i i u u u i u u
m m tri m m tri tri
Spectrum of digitized audio signal

Fig. 5

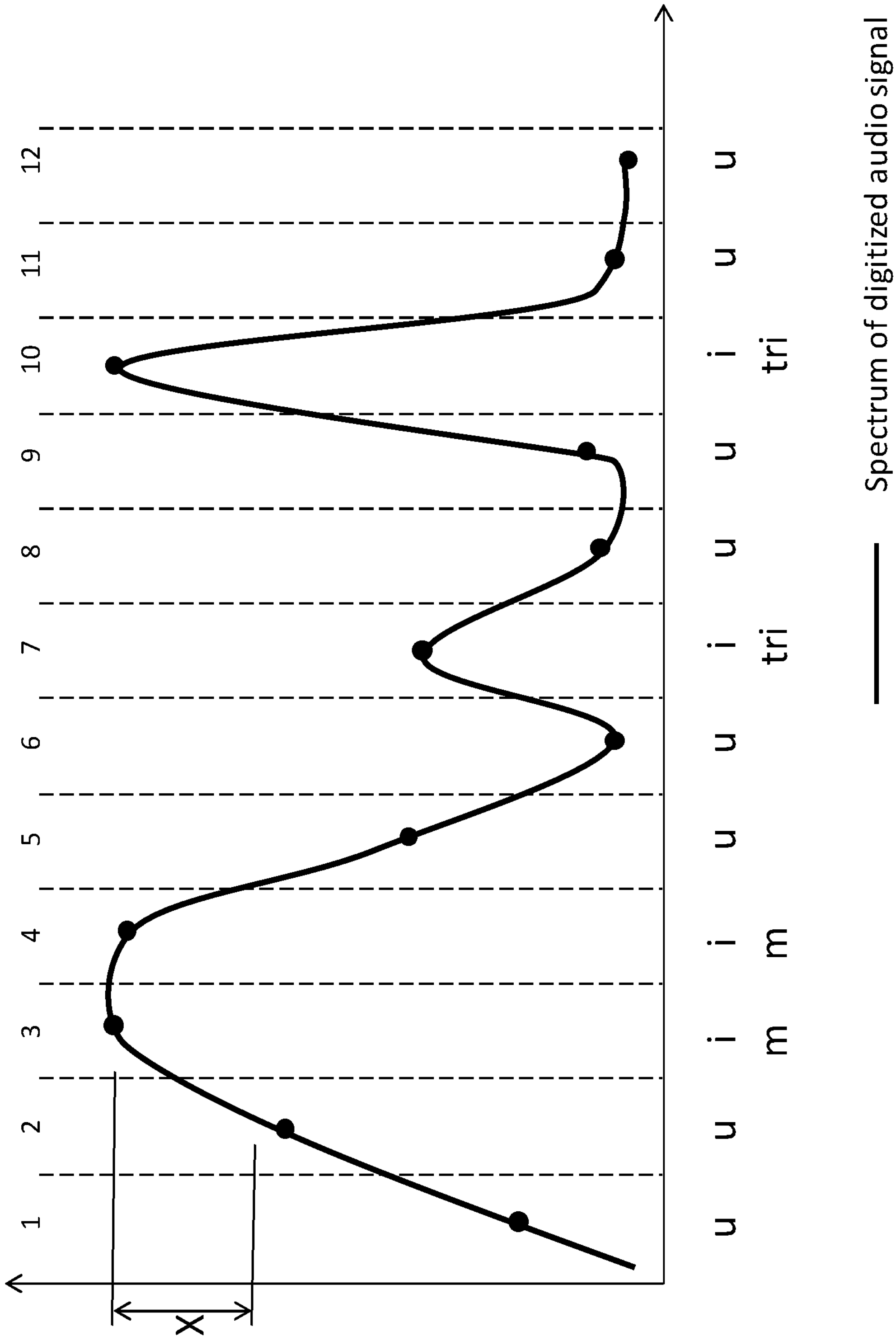
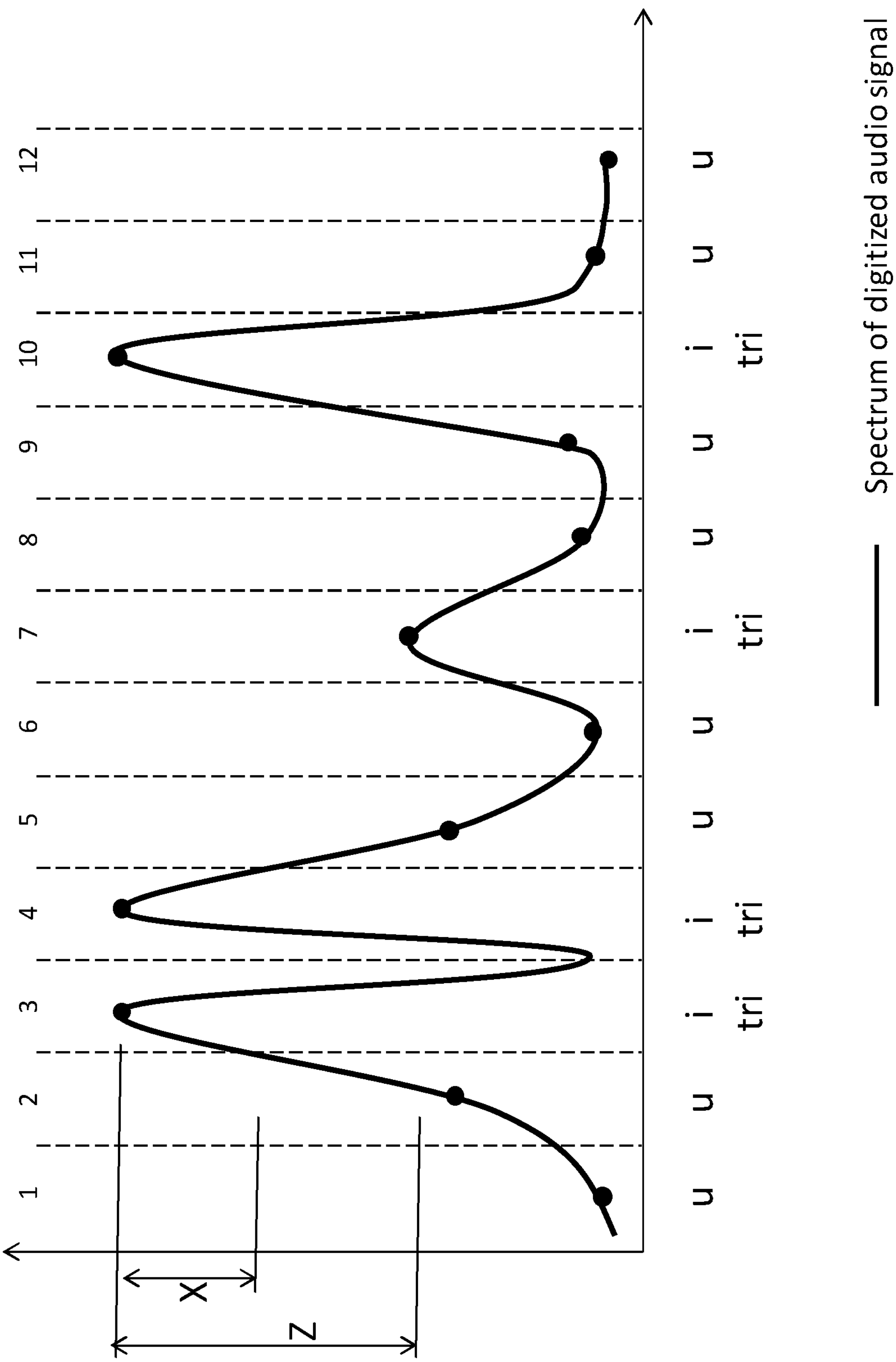

1
2
3
4
5
6
7
8
9
10
11
12
u u i i u u i u u i u u
m m
tri
tri
X
Spectrum of digitized audio signal

Fig. 6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2
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5
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9
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11
12
u
u
i
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u
u
i
u
u
i
u
u
tri
tri
tri
tri
X
Z
Spectrum of digitized audio signal

Fig. 7

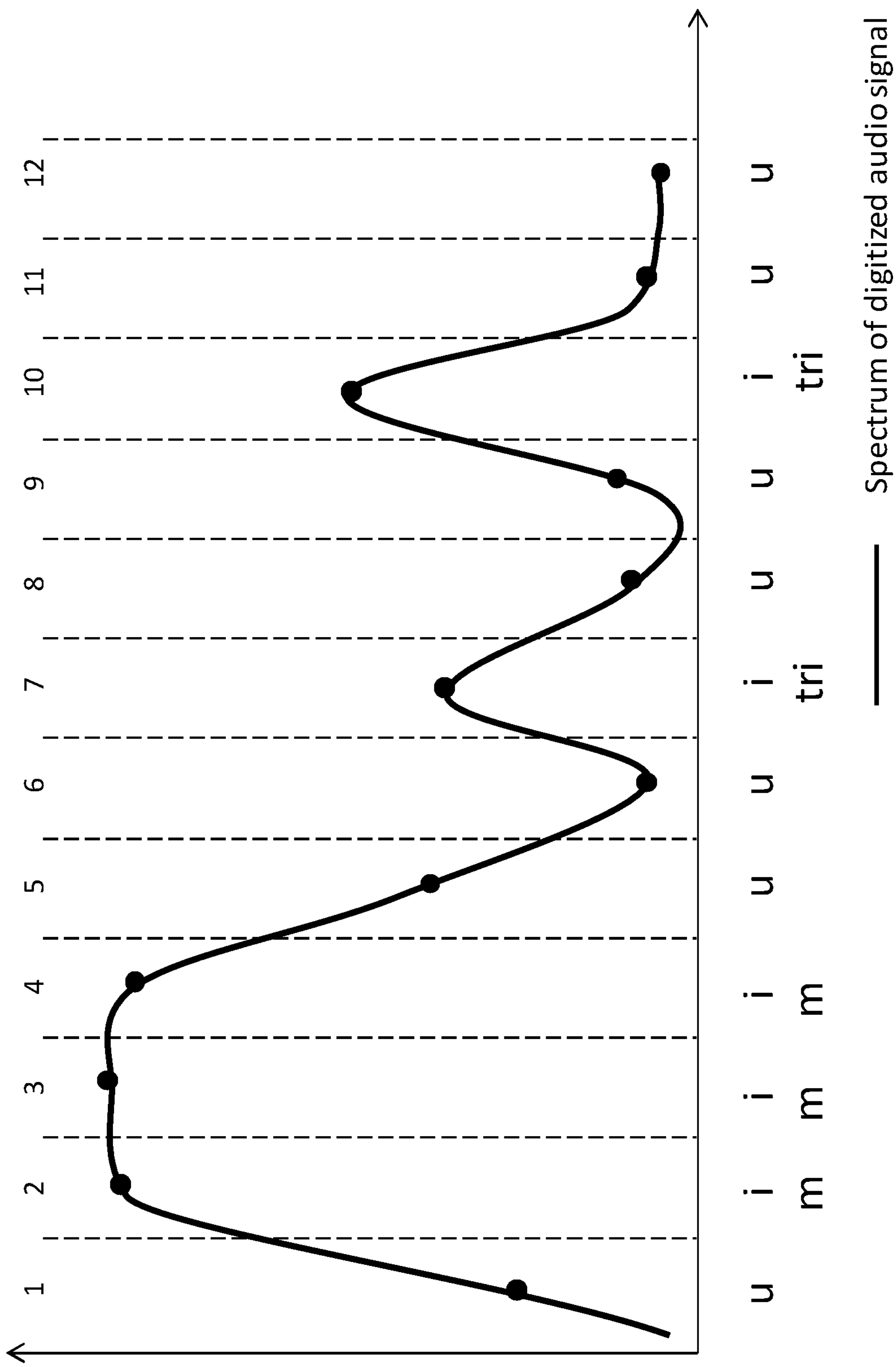
1
2
3
4
5
6
7
8
9
10
11
12
u
i
i
i
u
u
i
u
u
i
u
u
m
m
m
tri
tri
Spectrum of digitized audio signal

Fig. 8

REFERENCES CITED IN THE DESCRIPTION

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